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PERFORMANCE EVALUATION OF AN ADVANCED TRAFFIC CONTROL SYSTEM IN A DEVELOPING COUNTRY

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Abstract: Advanced Traffic Management Systems (ATMS) are one of the ITS technologies that have been promoted as a tool to ease congestion problems in many large cities in developing countries. However, it is unknown how poor lane discipline and complex road users interactions commonly observed in these cities affect the performance of these systems. Field studies are time consuming, expensive and can't capture important performance measures such as densities and queue lengths on all links and intersections in a network. An alternative approach is to use traffic simulations inside a controlled laboratory environment to evaluate these impacts. This paper presents initial results from traffic simulation experiments for the Bandung road network in Indonesia. A number of experiments were conducted to evaluate the performance of the ATMS against fixed time control under the same set of traffic demands. Model calibration and validation results provided a good degree of confidence in the models' abilities to reproduce field traffic conditions with the required accuracy. The simulation experiments results showed that the performance of ATMS in Bandung in terms of throughput and queue length is influenced by a number of localised conditions such as existence of CCTV surveillance and enforcement, location of critical intersections in network, distance to nearest intersection and level of side friction. The limitations of the study and future research directions are also presented.

Key words: Advanced Traffic Management Systems, Microscopic Traffic Simulation, Intelligent Transport Systems.

1. INTRODUCTION

Traffic congestion is increasingly becoming a severe problem in many large cities around the world. The problem is more complex in developing countries where cities are growing much faster than those in the developed world. The average annual population growth in developing countries is estimated at around 5 per cent compared to 0.7 per cent in developed countries (Sinha, 2000). Moreover, large cities in developing countries have low road network densities with poor conditions. The problem is further compounded by the interaction between a larger number of road users and transport modes.

Traffic congestion that causes poor traffic performance has negative impacts on economic productivity, environmental quality, and safety. Advanced Traffic Management Systems (ATMS) have been promoted as one of the ITS technologies that can help ease congestion problems in developing countries. However, it is unknown how poor network and geometric conditions, poor lane discipline and complex road user interactions can affect the performance of these systems.

In this paper, a simulation approach was adopted where road network conditions were compared with and without the ATMS under the same traffic demands. The traffic simulation software (AIMSUN) was used as a tool to develop microscopic traffic simulation model for the road network under consideration. A large road network in Bandung, Indonesia was used as a case study to evaluate the performance of an ATMS which was first implemented in Bandung in June 1997 as a pilot project. The system currently controls 117 signalised intersections out of 135 intersections in Bandung. Data collection was carried out during morning peak hour (7:00 – 8:00 am), afternoon peak hour (4:30-5:30 pm) and off peak hour (10:00-11:00 am). Two data sets were collected for use in this research. The first data set was used to develop and calibrate the model and the second data set was used for the validation. A number of statistical tests were used to determine the adequacy of the model in replicating traffic conditions.

2. ATMS IMPLEMENTATIONS IN DEVELOPING COUNTRIES

ATMS have been recognised as one of the most direct methods for relieving urban traffic congestion. ATMS are effective tools in coordinating traffic signals to reduce delay, stops and fuel consumption (Luk, 1992); maximise traffic throughput, respond to traffic demand (Giannakodakis, 1995) and improve safety (PATH, ITS DSS, 1998).

2.1 SCATS

There are a number of traffic control systems, for instance SCATS (Sydney Co-ordinated Adaptive Traffic System), SCOOT (Split Cycle Offset Optimisation Technique), BLISS (Brisbane Linked Intersection Signal System) and STREAMS (Synergised Transport Resources Ensuring an Advance Management System) that are currently used around the world.

SCATS was developed by New South Wales Department of Main Roads Australia. SCATS is a dynamic control system that can accommodate changing conditions using real time input from a number of different sources such as road detectors at the stop line, video cameras (CCTV), and pedestrian push buttons. This system updates intersection cycle length, stage split, and co-ordination with adjacent intersections within a road network to meet the variation in demand and improve traffic flow (US DOT, 2000). SCATS is the system currently running in Bandung and is the subject of evaluation in this study.

2.2 Local Specific Conditions

Cities in developing countries face more severe traffic problems than those in developed countries (Sinha, 2000). These cities have low network densities (only 3-8 per cent of the total city area compared to 20-25 per cent in large cities in developed countries such as London, Paris and New York). Furthermore, the limited road infrastructure has to serve city residents with high population densities and also high annual vehicle growth rate. To achieve a good traffic performance, the application and setting of SCATS in a developing country should take into consideration the specific local conditions that occur in these large cities. Some of these specific conditions include:

1. Large cities in developing countries have low road network densities with poor condition, for instance: short distance between intersections, poor road hierarchy and irregular pattern of road network with many intersections;

2. These cities experience much larger congestion levels because of the poor geometric conditions of intersections such as narrow lane widths;

3. Traffic conditions are further complicated due to a number of conditions, for instance:
   - many types of vehicles move in the same lane (poor lane discipline);
   - parking activity near intersections (also lack of enforcement);
   - road capacity is not fully utilised because of on street parking and street vendor activity on side walk that forces pedestrian to walk on the street;
   - land use patterns; and
   - bus and other public transport vehicles usually stop anywhere along the street.

3. AIMSUN Simulator

The Generic Environment for Traffic Analysis and Modeling (GETRAM) was used as a tool to develop microscopic traffic simulation model for the road network under consideration (TSS, 2004). GETRAM consists of TEDI as a traffic editor and AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non Urban Networks) as a microscopic traffic simulator. The benefits of using a computer model to simulate the "real world" conditions for predicting the performance of a traffic management scheme is well known. Computer modelling allows controlled experimentation and offers an economical way of studying the impact of traffic management measures before their implementation. The traffic data that are difficult and/or expensive to collect can also be predicted with computer models. This benefit can be realised only if measured data are available for calibrating the model. It is desirable that a base situation is first established by assessing whether the model reproduces traffic performance indices comparable to those measured in the field (Luk, Akcelik, et al., 1984). The movement of all individual vehicles through the network is simulated, and therefore a second by second image of the state of the network is produced. This process provides detailed information on network conditions.

4. DATA FOR DEVELOPING AND CALIBRATING MICROSCOPIC TRAFFIC SIMULATION MODELS

The field data required for the development of microscopic traffic simulation models include road and intersection geometric data plus traffic demand data. There are two types of traffic demand data that can be used in AIMSUN, the traffic flow at the input sections or O-D matrices. The traffic flows at intersections were used in this study as the traffic demand data. The main limitation of this approach is that it does not allow for route choice behaviour to be modelled but that was outside the scope of this particular project due to the difficulty of getting accurate O-D data. The roads and intersections geometric data was obtained from Bandung road map, Bandung Area Traffic Control, Final System Design (AWA Plessey, 1996) and direct survey. This data was used to create a digitised Bandung road network map. While traffic demand data was estimated from data recorded by the SCATS system using mini computer in the Bandung Traffic Control Room, and was obtained from direct road survey when the road loop detectors were not available. Data collection was carried out at all signalised intersections connected to SCATS during morning peak hour (7:00 – 8:00 am), afternoon peak hour (4:30-5:30 pm) and off peak hour (10:00-11:00 am) in Bandung, Indonesia. SCATS currently controls 117 signalised intersections out of 135 signalised intersections in Bandung. All signalised intersections connected to SCATS are divided into two regions, the North Region and the South Region. The observed intersections in this research were the 90 signalised intersections connected to SCATS. The data which were obtained from SCATS was recorded every 15 minutes and include throughput data of each loop detector at each intersection plus queue length data from a number of critical intersections with CCTV. Two data sets were collected to used in this research. The first data set was used to develop and calibrate the model and the second data set was used for validation.

5. DATA FOR THE VALIDATION OF TRAFFIC SIMULATION MODELS

Model validation is important to ensure that the microscopic traffic simulation model replicates the existing local geometric and traffic conditions. The validation data set should be independent of the first data set used for developing the model. This second data set used for validation was collected at different times from the data used for calibration but data collection was carried out at the same 90 signalised intersections and the same time period: morning peak hour (7:00 – 8:00 am), afternoon peak hour (4:30-5:30 pm) and off peak hour (10:00-11:00 am). There were 4-14 loop detectors at each signalised intersection for vehicle detection. The throughput data from each loop detector at each signalised intersection in addition to queue length data of a number of signalised intersections with CCTV surveillance is believed to be one of the largest sets of “real world” data available for the development and validation of microscopic traffic simulation models. The road network map of Bandung with intersections connected to and isolated from SCATS control is shown in Figure 1.

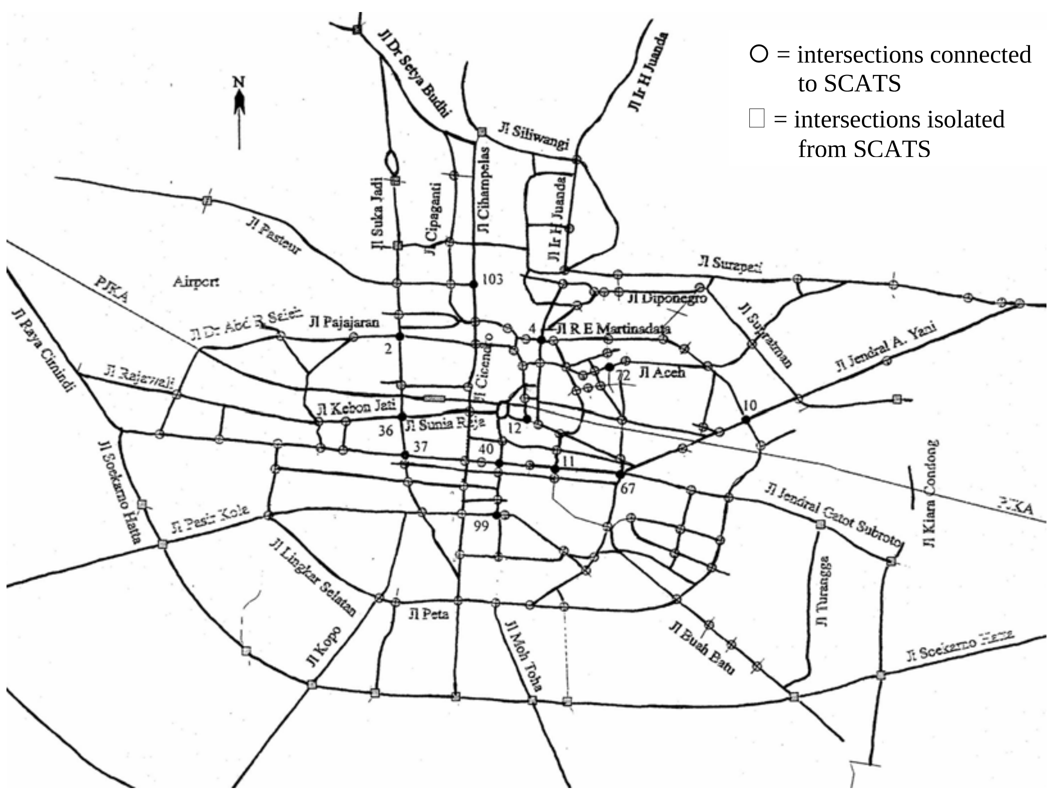

Figure 1. Signalised Intersections in Bandung (Awa Plessey, 1996)

6. A FRAMEWORK TO EVALUATE THE PERFORMANCE OF ATMS

6.1 Model Development

The first step of developing the microscopic traffic simulation model is to create a Bandung digitised road network map which includes road infrastructure and geographical boundaries. The digitised map is then used for coding the road network including geometric layout, roads, lanes, lane width, intersections, and turning movements. Turning movements, turning proportions, phases, green times, amber time, all red time, and cycle times were obtained from the traffic count data.

The second step is to calibrate the model to replicate the existing traffic performance. The aim of calibration is to ensure that the model reflects as accurately as possible the existing road conditions. The process of calibration allowed for the adjustment of parameters used within the model including parameters that affect the behaviour of the vehicle-driver-unit (DVU), for example, reaction time, size of vehicles, speed of vehicles, gap acceptance and driver behaviour parameters. Parameters used within the Bandung microscopic traffic simulation models are presented in Table 1.

Table 1. Parameters Used within the Bandung Microscopic Traffic Simulation Models

Parameter	Value	Unit
Global Parameters:		
Driver's reaction time	0,75	s
Reaction time at stop	0,75	s
Queue up speed	1	m/s
Queue living speed	4	m/s
% overtake	90	%
% recover	95	%
Local Section Parameters:		
Maximum speed	*	km/h
Visibility distance	*	s
Lane changing distances	*	s
Particular Vehicle Tipe Parameters:		
Maximum desired speed	50	km/h
Minimum distance between vehicles	0,5	m
Give way time	2	s

* = specific to each section

Once the model was developed, a number of statistical tests including Paired T-test, Two Sample T-test, Regression Analysis, Analysis of Variance, and Correlation Tests were used to determine the adequacy of the model in replicating traffic conditions. In Paired T-test, H_0:δ=0 is excepted if the difference between the simulated and the measured data are zero. This condition is very difficult to reach, especially for a large number of paired data. If H_0:δ=0 is rejected, then the Two sample T-test, wherein H_0:w_i=v_i (simulated and measured data are statistically equal), will be performed. These tests are necessary to determine the suitability of the model for the task. Two performance measures i.e. traffic flow and queue length have been tested using statistical methods. The results of model calibration tests are presented in Tables 2-3. The statistical tests clearly show that the calibrated models reproduced field conditions with an acceptable degree of confidence.

Table 2. The Results of Model Calibration Tests with Traffic Flow as the Performance Measure

Morning Peak Hour	7:00-7:15 am	7:30-7:45 am	7:15-730 am	7:45-8:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	595	594	589	584
simulated average flow (w_i, veh/h, i = 165)	616	598	556	530
s_{di}	72.486	45.785	71.864	97.064
t_{m-1}	9.483	11.833	9.802	9.569
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.706	0.150	-1.097	-1.763
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 4.279 + 0.942 x_{ij}	y_{ij} = 5.073 + 0.984 x_{ij}	y_{ij} = 39.57 + 0.989 x_{ij}	y_{ij}= 54.335 + 0.998 x_{ij}
• Correlation Coefficient	0.976	0.987	0.976	0.960
• Coefficient of Determination	0.953	0.975	0.953	0.922
Off Peak Hour	10:00-10:15 am	10:15-10:30 am	10:30-10:45 am	10:45-11:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	622	624	626	617
simulated average flow (w_i, veh/h, i = 165)	627	622	625	576
s_{di}	48.911	47.989	37.416	93.857
t_{m-1}	10.289	9.370	12.195	7.903
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.200	-0.058	-0.024	-1.445
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} =1.98	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 21.069 + 0.957 x_{ij}	y_{ij} = 20.79 + 0.969 x_{ij}	y_{ij} = 24.588 + 0.962 x_{ij}	y_{ij} = 54.193 + 0.978 x_{ij}
• Correlation Coefficient	0.987	0.988	0.991	0.961
• Coefficient of Determination	0.974	0.976	0.983	0.924
Afternoon Peak Hour	4:30-4:45 pm	4:45-5:00 pm	5:00-5:15 pm	5:15-5:30 pm
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	576	575	563	507
simulated average flow (w_i, veh/h, i = 165)	654	605	507	430
s_{di}	157	75.313	115.122	128.15
t_{m-1}	7.968	11.048	8.999	9.956
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	2.589	1.012	-1.913	-2.605
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	accept H_0	accept H_0	reject H_0
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 2.61	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 30.891 + 0.834 xi_{ij}	y_{ij} = 24.278 + 0.910 x_{ij}	y_{ij} = 99.331 + 0.916 x_{ij}	y_{ij} = 123.6 + 0.891 x_{ij}
• Correlation Coefficient	0.919	0.974	0.945	0.932
• Coefficient of Determination	0.845	0.949	0.893	0.869

Table 3. The Results of Model Calibration Tests with Queue Length as the Performance Measure

Morning Peak Hour	7:00-7:15 am	7:30-7:45 am	7:15-730 am	7:45-8:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	12	12	14	15
simulated average queue length (w_i,veh, i=8)	12	11	14	19
s_{di}	1.069	1.126	0.641	6.479
t_{m-1}	3.969	4.710	8.275	2.019
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	reject H_0	reject H_0	accept H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	-0.738	-0.897	0.099	
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	accept H_0	accept H_0	accept H_0	
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 3.252 + 0.785 x_{ij}	y_{ij} = 3.393 + 0.791 x_{ij}	y_{ij} = 3.888+ 0.705 x_{ij}	$y_{i\,j}$= 9.772 + 0.235 x_{ij}
• Correlation Coefficient	0.824	0.864	0.892	0.847
• Coefficient of Determination	0.680	0.747	0.796	0.718
Off Peak Hour	10:00-10:15 am	10:15-10:30 am	10:30-10:45 am	10:45-11:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	13	11	12	13
simulated average queue length (w_i,veh, i=8)	13	11	12	12
s_{di}	1.188	1.309	1.356	1.389
t_{m-1}	3.274	2.160	1.825	2.546
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	accept H_0	accept H_0	reject H_0
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 3.50	accept H_0	accept H_0	accept H_0	accept H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.299			-0.162
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} =2.37	accept H_0			accept H_0
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 1.311 + 0.869 x_{ij}	y_{ij} = -1.229 + 1.159 x_{ij}	y_{ij} = -1.294 + 1.165 x_{ij}	y_{ij} = 0.691 + 0.964 x_{ij}
• Correlation Coefficient	0.864	0.874	0.930	0.900
• Coefficient of Determination	0.746	0.764	0.864	0.811
Afternoon Peak Hour	4:30-4:45 pm	4:45-5:00 pm	5:00-5:15 pm	5:15-5:30 pm
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	13	11	12	13
simulated average queue length (w_i,veh, i=8)	13	11	13	20
s_{di}	0.744	0.518	2.669	13.12
t_{m-1}	2.376	3.416	1.722	1.752
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	reject H_0	accept H_0	accept H_0
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 3.50	accept H_0	accept H_0		
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.185	-0.185		
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	accept H_0	accept H_0		
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 3.641 + 0.708 xi_{ij}	y_{ij} = 2.821 + 0.746 x_{ij}	y_{ij} = 4.766 + 0.543 x_{ij}	y_{ij} = 9.256 + 0.186 x_{ij}
• Correlation Coefficient	0.939	0.956	0.936	0.872
• Coefficient of Determination	0.881	0.915	0.877	0.760

The third step in model development was to validate the calibrated microscopic traffic simulation model using field data. Again, a number of statistical tests were used to determine the adequacy of the model in replicating traffic conditions. This step is required to demonstrate the validity of the calibrated models and show that these models did not only perform well for the data sets on which they have been calibrated. A second data set of flow measurements (which was not used for calibration) was collected from the field and compared to the flows generated by the simulator. The statistical results for the validation task are shown in Tables 4-5. All tests showed that the field and simulated measurements are essentially the same and hence the hypothesis that the means of the two distributions are different was rejected. Tables 2 - 5 show that the model outputs were consistently accurate for both the morning peak, inter-peak and afternoon peak periods.

Table 4. The Results of Model Validation Tests with Traffic Flow as the Performance Measure

Morning Peak Hour	7:00-7:15 am	7:30-7:45 am	7:15-730 am	7:45-8:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	588	589	590	585
simulated average flow (w_i, veh/h, i = 165)	594	589	583	556
s_{di}	49.274	38.747	44.063	68.787
t_{m-1}	10.402	12.445	11.318	9.778
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.177	-0.008	-0.226	-0.943
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 7.6295 + 0.978 x_{ij}	y_{ij} = 2.49 + 0.996 x_{ij}	y_{ij} = 4.644 + 1.004 x_{ij}	y_{ij} = 38.173 + 0.983 x_{ij}
• Correlation Coefficient	0.987	0.990	0.989	0.978
• Coefficient of Determination	0.974	0.981	0.977	0.956
Off Peak Hour	10:00-10:15 am	10:15-10:30 am	10:30-10:45 am	10:45-11:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	613	619	617	615
simulated average flow (w_i, veh/h, i = 165)	612	619	607	584
s_{di}	44.900	41.592	32.625	80.103
t_{m-1}	11.319	10.519	14.002	8.249
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	-0,023	0,014	-0,356	-1,066
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 24.697 + 0.961 x_{ij}	y_{ij} = 14.832 + 0.975 x_{ij}	y_{ij} = 17.734 + 0.988 x_{ij}	y_{ij} = 53.647 + 0.961 x_{ij}
• Correlation Coefficient	0.988	0.990	0.992	0.971
• Coefficient of Determination	0.976	0.979	0.984	0.943
Afternoon Peak Hour	4:30-4:45 pm	4:45-5:00 pm	5:00-5:15 pm	5:15-5:30 pm
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average flow (v_i, veh/h, i = 165)	581	584	578	530
simulated average flow (w_i, veh/h, i = 165)	640	617	536	454
s_{di}	146.553	57.530	112.673	134.58
t_{m-1}	7.645	12.103	7.849	9.401
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	reject H_0	reject H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	2.011	1.112	-1.407	-2.604
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 1.98	reject H_0	accept H_0	accept H_0	reject H_0
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 2.61	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured flow, x_{ij}= simulated flow)	y_{ij} = 50.319 + 0.829 x_{ij}	y_{ij} = 8.439 + 0.933 x_{ij}	y_{ij} = 77.461 + 0.932 x_{ij}	y_{ij} = 131.55 + 0.877 x_{ij}
• Correlation Coefficient	0.925	0.984	0.945	0.927
• Coefficient of Determination	0.856	0.969	0.893	0.859

Table 5. The Results of Model Validation Tests with Queue Length as the Performance Measure

Morning Peak Hour	7:00-7:15 am	7:30-7:45 am	7:15-730 am	7:45-8:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	13	13	13	13
simulated average queue length (w_i,veh, i=8)	12	12	13	19
s_{di}	0.926	1.036	0.756	8.417
t_{m-1}	4.583	3.416	3.742	1.806
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	reject H_0	reject H_0	accept H_0
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 3.50	reject H_0	accept H_0	reject H_0	
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	-0.612	-0.826	0.000	
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	accept H_0	accept H_0	accept H_0	
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 4.267 + 0.713 x_{ij}	y_{ij} = 3.091+ 0.818 x_{ij}	y_{ij} = 1.342+ 0.895 x_{ij}	y_{ij}= 9.090 + 0.223 x_{ij}
• Correlation Coefficient	0.957	0.948	0.877	0.846
• Coefficient of Determination	0.916	0.898	0.768	0.715
Off Peak Hour	10:00-10:15 am	10:15-10:30 am	10:30-10:45 am	10:45-11:00 am
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	13	11	12	11
simulated average queue length (w_i,veh, i=8)	13	11	12	10
s_{di}	0.641	0.916	0.535	0.641
t_{m-1}	4.965	4.245	2.646	4.965
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	reject H_0	reject H_0	reject H_0
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} =3.50	reject H_0	reject H_0	accept H_0	reject H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.244	-0.366	-0.176	-0.827
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} =2.37	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 1.787 + 0.832 x_{ij}	y_{ij} = -0.773 + 1.109 x_{ij}	y_{ij} = -0.082 + 1.029 x_{ij}	y_{ij} = 1.005 + 0.963 x_{ij}
• Correlation Coefficient	0.974	0.818	0.985	0.832
• Coefficient of Determination	0.949	0.669	0.970	0.692
Afternoon Peak Hour	4:30-4:45 pm	4:45-5:00 pm	5:00-5:15 pm	5:15-5:30 pm
• Paired T - test (H_0: δ_i=0, H_a : $\delta_i \neq 0$)				
measured average queue length (v_i, veh, i=8)	13	12	11	13
simulated average queue length (w_i,veh, i=8)	13	12	11	15
s_{di}	0.535	0.641	0.744	4.310
t_{m-1}	2.646	3.862	2.376	2.625
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	reject H_0	reject H_0	reject H_0	reject H_0
H_0: δ_i=0 : $t_{m-1,\alpha/2\ \alpha=0.01}$, t_{m-1} = 3.50	accept H_0	reject H_0	accept H_0	accept H_0
• Two Sample T-test (H_0:w_i=v_i, H_a:$w_i \neq v_i$)				
t_{m-1}	0.400	-0.162	-0.462	1.629
H_0: w_i=v_i: $t_{m-1,\alpha/2\ \alpha=0.05}$, t_{m-1} = 2.37	accept H_0	accept H_0	accept H_0	accept H_0
• Regression Analysis (y_{ij}= measured queue length, x_{ij}= simulated queue length)	y_{ij} = 2.091 + 0.818 xi_{ij}	y_{ij} = 3.281 + 0.729 x_{ij}	y_{ij} = 2.819 + 0.767 x_{ij}	y_{ij} = 6.855 + 0.408 x_{ij}
• Correlation Coefficient	0.940	0.924	0.962	0.966
• Coefficient of Determination	0.884	0.854	0.926	0.933

The results of the calibration and validation tasks provided a good degree of confidence in the models' abilities to reproduce field traffic conditions with the required accuracy and also showed that these models are a suitable tool for use in this study. It should also be pointed out here that the scale of model development is quite large and required a substantial amount of resources and effort to construct, calibrate and validate the models. The Bandung North Region microscopic traffic simulation model consisted of 1009 links and 426 nodes including 48 intersections under SCATS control. The Bandung South Region Model consisted of 604 links and 262 nodes including 42 intersections under SCATS control.

6.2 Application of the Validated Microscopic Traffic Simulation Model

After the microscopic traffic simulation model was validated, the network performance under SCATS was compared to a fixed cycle time system (without SCATS) using traffic simulation. This step was undertaken for three time periods: morning peak, afternoon peak and off peak for both regions in Bandung.

The next task was to explore the effect of geometric and traffic conditions in Bandung on the performance of SCATS. Geometric and traffic characteristics that might have significant influence on the throughput and queue length at intersections included the number of intersection legs, existence of CCTV at intersection, the location of intersection (in CBD or in residential area), the distance to the closest intersection, volume capacity ratio of the road, and level of side friction in connection with on street parking and on street vendor activities. The traffic performance measurements i.e. throughput, queue length, and travel time were obtained from microscopic traffic simulation model whereas the geometric and traffic conditions were observed from field data.

7. INITIAL EVALUATION RESULTS

Results of running the validated models with and without SCATS for 90 signalised intersections in Bandung indicated a variety of changes in throughputs and queue lengths at intersections. Validated models were developed for each region. In the North Region, SCATS controlled 48 signalised intersections whereas it controlled 42 signalised intersections in the South Region. Models were also developed during morning peak, afternoon peak and off peak. The results of running the validated models are presented in Tables 6-7.

In North Region, 24 out of the 48 signalised intersections experienced a decrease in throughput and 35 out of 48 signalised intersections experienced increases in queue length. The North Bandung results presented in Table 6 showed that throughput was found to decrease by 12 per cent during morning peak, increase by 4.61 percent during off peak and increase by 4.35 percent during afternoon peak. On average, there is decrease of 1 per cent in throughput (insignificant) and an increase of 16 per cent in maximum queue length.

In South Region, 25 out of the 42 signalised intersections decreased in throughput and 38 out of 42 signalised intersections increased in queue length. The results for South Bandung road network presented in Table 6 showed that throughput decreased 1 per cent during morning peak (insignificant); decreased by 7 per cent during off peak and increased 3 per cent during evening peak. On average, there was a decrease of 1.8 per cent in throughput and an increase of 17 per cent in maximum queue length.

Table 6. Flow Difference and Queue Length Difference between With and Without SCATS in Bandung Road Network

Region	average flow difference (%)				average queue length difference (%)							
	morning peak	off peak	afternoon peak	average	morning peak		off peak		afternoon peak		average	
					mean	max	mean	max	mean	max	mean	max
North	-12,00	4,61	4,35	-1,01	40,05	26,60	7,29	13,03	162,07	8,66	69,80	16,10
South	-1,06	-7,09	2,74	-1,80	3,01	12,57	41,42	29,30	-6,13	9,45	12,77	17,11

The results presented in Table 7 were aimed at demonstrating how the ATMS performance is influenced by a number of factors such as number of legs on intersection, existence of CCTV and enforcement, distance to nearest intersection etc. The results showed that SCATS control at intersections with 5 legs had the largest benefits with an increase in throughput of around 6.9 per cent in the North Region and 18.6 per cent in South Region. The performance of SCATS was found to be superior in the CBD area at closely spaced intersections and on roads with high volume to capacity ratios and with low level of side friction. These results are consistent with findings from other studies conducted in various cities around the world.

Table 7. Flow Difference and Queue Length Difference between With and Without SCATS in Bandung Road Network - Based on Classification

no.	classification	flow difference (%)				queue length difference (%)							
		morning peak	off peak	afternoon peak	average	morning peak		off peak		afternoon peak		average	
						mean	max	mean	max	mean	max	mean	max
	North Region												
1	number of leg intersections:												
	3 leg intersections	-8,96	3,35	11,45	1,94	248,85	36,43	84,86	14,64	104,11	19,15	145,94	23,41
	4 leg intersections	-12,06	6,43	-0,40	-2,01	85,48	36,22	123,25	36,26	161,99	34,71	123,57	35,73
	5 leg intersections	0,90	0,55	19,22	6,89	60,35	49,14	138,25	52,88	-1,99	22,63	65,54	41,55
2	the existence of CCTV:												
	without CCTV	-10,03	5,47	4,92	0,12	147,83	37,72	113,89	29,08	140,27	28,52	133,99	31,77
	with CCTV	-16,33	-0,55	0,05	-5,61	59,26	23,60	56,04	32,54	50,58	31,35	55,29	29,16
3	Location:												
	CBD	-8,76	2,63	8,29	0,72	136,84	29,07	98,53	25,01	87,90	19,74	107,76	24,61
	Residential Area	-16,00	13,39	-7,76	-3,46	160,65	62,97	149,77	43,69	291,95	58,81	200,79	55,15
4	the distance to the closest int:												
	100 m - 200 m	-6,91	8,49	7,85	3,14	36,14	22,48	77,75	45,30	39,05	33,80	50,98	33,86
	200 m - 300 m	-21,50	4,59	5,56	-3,78	341,08	66,73	191,32	38,15	104,31	17,03	212,24	40,64
	300 m - 400 m	-0,77	4,67	14,36	6,09	12,58	3,78	11,66	5,45	33,17	7,67	19,13	5,63
	> 400 m	-7,93	4,59	-1,73	-1,69	90,79	35,00	107,54	29,01	235,29	45,63	144,54	36,55
5	v/c of the road												
	high v/c	-8,35	5,52	6,52	1,23	99,15	30,60	40,75	16,94	124,37	23,83	88,09	23,79
	low v/c	-18,30	3,46	-2,63	-5,82	99,15	30,60	40,75	16,94	124,37	23,83	88,09	23,79
6	level of side friction												
	high level of side friction	-11,59	2,87	3,95	-1,59	154,12	34,35	115,84	32,14	109,05	25,73	126,34	30,74
	low level of side friction	-9,26	7,31	5,27	1,11	130,46	39,32	104,71	26,45	160,27	31,65	131,81	32,47
	South Region												
1	number of leg intersections:												
	3 leg intersections	-2,98	-6,44	-4,13	-4,52	65,31	27,05	57,21	24,44	60,48	27,34	61,00	26,28
	4 leg intersections	-1,11	-8,40	1,96	-2,52	83,53	35,92	180,78	57,95	70,14	28,58	111,48	40,81
	5 leg intersections	11,14	-2,73	47,33	18,58	-12,19	5,09	231,61	89,32	-28,05	-1,91	63,79	30,83
2	the existence of CCTV:												
	without CCTV	-1,72	-8,90	-0,63	-3,75	74,45	29,56	157,60	49,35	71,30	30,01	101,11	36,31
	with CCTV	2,12	-1,86	16,91	5,72	97,80	57,07	163,55	70,08	33,97	13,25	98,44	46,80
3	Location:												
	CBD	-1,37	-5,56	2,41	-1,51	84,90	36,83	118,35	42,96	70,23	29,73	91,16	36,51
	Residential Area	0,69	-30,08	-3,18	-10,86	10,15	1,81	539,37	141,15	25,45	7,47	191,66	50,14
4	the distance to the closest int:												
	100 m - 200 m	1,67	-2,82	19,18	6,01	146,43	71,02	179,61	76,61	-4,15	-9,95	107,30	45,89
	200 m - 300 m	2,07	-4,32	9,40	2,38	73,23	29,40	136,15	55,33	45,48	41,99	84,96	42,24
	300 m - 400 m	-3,07	-14,17	-4,95	-7,40	87,84	30,70	255,11	77,67	99,60	28,37	147,52	45,58
	> 400 m	-2,14	-6,17	-1,74	-3,35	50,44	26,08	84,44	22,60	70,78	31,55	68,56	26,74
5	v/c of the road:												
	high v/c	0,83	-4,84	6,32	0,77	74,56	32,47	96,12	35,60	54,51	18,42	75,06	28,83
	low v/c	-3,37	-11,26	-3,01	-5,88	81,32	34,62	227,01	70,70	78,56	37,73	128,97	47,68
6	level of side friction:												
	high level of side friction	-1,91	-6,00	-0,92	-2,94	69,98	30,35	97,00	36,15	69,56	33,14	78,84	33,22
	low level of side friction	0,48	-12,13	8,12	-1,18	95,19	40,51	295,54	88,35	57,95	15,28	149,56	48,05

8. STUDY LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

One of the main advantages of a system like SCATS is its ability to adjust traffic signal timings in real-time in response to variations in demand. The data collected for SCATS in this study reflects a certain specific demand that was observed at the time of surveys. The traffic signal settings that were observed for SCATS are only applicable to those demands. The main limitation of the results reported in this study is that SCATS was not interfaced directly to the simulator. The Roads and Traffic Authority (RTA) of New South Wales initiated the development of a simulation interface to its SCATS signal control system a few years ago. The basic concept for this work was to use simulation models to replace the real world actuation of detectors and for the simulator to respond in a realistic manner to signal information received from SCATS. The SCATS simulation version (SCATSIM) is exactly the same as SCATS except it runs faster than real time. Unfortunately, the AIMSUN-SCATS interface was not available in time for use in this study but will be considered in future efforts. Current efforts are also focused on evaluating the performance of the system in terms of its impacts on travel times and how it responds to simulated incidents, construction work and other events that may decrease the capacity of the road network. Another limitation of the approach reported in this study is that turning counts at signalised intersections were used to obtain the traffic demand data. This limited the opportunity to study any routing effects on the network. However, given that the whole network was simulated and that traffic at all intersections was considered, this is not considered a major disadvantage in the context of this study but will need to be reconsidered in future studies.

9. CONCLUSIONS

This study explored the evaluation of the performance of an adaptive traffic control system (SCATS) in a large city in a developing country. The results presented in this paper were obtained using a simulation approach. Initial results showed that SCATS performance varied substantially according to specific local conditions which were found to have an influence on traffic performance. The main limitation of the study was the inability to interface SCATS to the traffic simulator but it is hoped that this will be possible in future research work. Efforts are also currently underway to further explore the performance of the system using a wider range of analysis to include evaluations of travel time benefits and impacts of incidents and other events which may reduce the capacity of the network.

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